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BRAZING INVESTIGATION OF SEVERAL CANDIDATE MATERIALS FOR THRUST CHAMBER AND HEAT EXCHANGER APPLICATIONS

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BRAZING INVESTIGATION OF SEVERAL CANDIDATE MATERIALS FOR THRUST CHAMBER AND HEAT EXCHANGER APPLICATIONS

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Project 281

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R. C. Kay, C. A. Drury, and A. Mardarian - Mechanical Property Tests

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R. C. Kay and J. C. Reeves - Compilation and Analyses of Data

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I. SUMMARY

Brazing studies were conducted on candidate alloys for thrust chamber and heat exchanger applications. The objectives of these studies were to improve the technique for structurally joining Rene' 41 to itself and other alloys and to develop procedures for brazing aluminum and titanium alloys.

Rene' 41, L-605, and 6061 aluminum alloy sheet materials were evaluated in material thickness of 0.010 inch, and A110AT titanium in material thickness of 0.031 inch. Titanium (3Al-2.5V) in thicknesses (tube) of 0.002-inch wall, Type 321 stainless steel 0.0025-inch wall tubes, and 0.010/0.020-inch Rene' 41 sheet were evaluated on a preliminary basis only, utilizing the induction brazing process.

Vacuum furnace brazing was utilized for joining Rene' 41, L-605, 6061 aluminum, and A110AT titanium materials. Induction brazing (inert gas atmosphere) was utilized for joining 6061 aluminum, A110AT titanium, 3Al-2.5V titanium, 321 stainless, and Rene' 41 materials.

The results are summarized as follows:

1. The results exhibited by vacuum-furnace-brazed Rene' 41 to Rene' 41, Rene' 41 to L-605 tensile specimens at room temperature and 1500°F were lower than the properties obtained in previous tests. Bend specimens were unsatisfactory at both room temperature and 1500°F.

2. Both vacuum-furnace and induction-brazed 6061 aluminum specimens were unsatisfactory due to instantaneous formation of irreducible aluminum oxides on the brazing surfaces. This investigation eliminated the use of flux because of potential contamination problems during the actual fabrication of heat exchangers.

3. Furnace brazing of A110AT titanium sheet material was unsatisfactory. Induction brazing of A110AT titanium sheet material produced a few specimens, but subsequent testing indicated extreme joint brittleness.

4. Preliminary induction brazing of Rene' 41 to Rene' 41 sheet material indicated excellent joint strengths. Fracture consistently occurred in the base metal. The tests were conducted at room temperature.

5. Preliminary induction brazing and testing of 3Al-2.5V titanium 0.002-inch wall tubing resulted in base metal failure at room temperature. The brazing alloys were AGC-7 (70 gold, 22 nickel, 8 palladium) and fine silver (99.9 + purity).

6. Preliminary induction brazing and testing of 0.0025-inch wall Type 321 stainless steel tubing indicated the brazed joint to be stronger than the base metal at room temperature. The brazing alloy used was Coast Metals 52 (AMS 4778), nickel base, chrome-free, high temperature alloy.

II. INTRODUCTION

Previous brazing studies conducted at The Marquardt Corporation consisted principally of the evaluation of various commercial and noncommercial filler material combinations that would structurally join Rene' 41. By the process of elimination, the AGC-1 composition (gold, nickel, palladium) formulated by the Aerojet-General Corporation was selected. Although the previous brazing methods were adequate for preliminary investigations, additional effort was required to develop optimum brazing techniques for thrust chamber and heat exchanger fabrication.

The purposes of the program reported herein were (1) the improvement of brazing techniques for the structural joining of Rene' 41 to itselft and other alloys, and (2) the development of procedures for brazing aluminum and titanium alloys.

The regeneratively cooled thrust chamber under study was originally designed for fabrication from Rene' 41. Later data indicated the feasibility and practicability of substituting the L-605 or Hastelloy C alloys in selected areas. Since Hastelloy C was being evaluated in other programs, it was decided to include only L-605 along with Rene' 41 in this brazing study. As the requirements for joining the regeneratively cooled thrust chamber indicated the use of multicycle brazing, various compositions of AGC brazing alloys were included for evaluation in the program.

Parallel brazing studies of 6061 aluminum and A110AT titanium were required to support the heat exchanger materials evaluation effort, particularly as applicable to structural joining.

This report includes tables, sketches, and photomicrographs of tensile butt brazed joints reflecting data generated from both brazing studies. Bend test results of brazed specimens are included. Also included are photographs of 3Al-2.5V titanium and Type 321 stainless steel tubing brazed in similar and dissimilar combinations.

III. MATERIALS

A. Thrust Chamber Materials

The chemical compositions of the Rene' 41 and L-605 alloys are shown in Table I. The brazing alloys selected for joining Rene' 41 to Rene' 41 and Rene' 41 to L-605 combinations were AGC-1, AGC-4, and AGC-7. The chemical compositions for these alloys are shown in Table II.*

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* Other data for the brazing alloys are shown in Table II. These data include form, melting point, and normal brazing temperature range.

B. Heat Exchanger Materials

The chemical compositions of the 6061 aluminum and A110AT titanium alloys are shown in Table I. The brazing alloy selected for joining 6061 aluminum was Alcoa 718 (AMS 4185). Fine silver and AGC-7 were used for joining the A110AT titanium material (see Table II).*

IV. PREPARATION OF TEST SPECIMENS

Suitable quantities of Rene' 41, L-605, 6061 aluminum, and A110AT specimens, each 1 by 4 1/2 inches, were procured and prepared as shown in Figure 1-A. Figure 1-B shows the prepared specimens as brazed, and Figure 1-C shows the specimens after machining. Figure 2 shows the dimensional configuration of the brazed specimens prior to testing, and Figure 3 shows the bend test specimen configuration.

V. CLEANING PROCEDURES

After preparation, all Rene' 41, L-605, 6061 aluminum, and A110AT specimens were cleaned in accordance with the procedures shown in Table III.

VI. EQUIPMENT

A. Vacuum Brazing Equipment

The equipment used for vacuum brazing consisted of a hot wall furnace with a retort designed to contain a constant vacuum pressure. The specimens to be brazed were placed in the retort, which was then sealed by a water-cooled rubber gasket. The retort was evacuated to a pressure of one micron or less, and the specimens were heated to the brazing temperature. Chromel-alumel thermocouples were used to record both furnace temperature and specimen temperature.

B. Induction Brazing Equipment

Heating of the induction brazing specimens was performed in an argon atmosphere. The specimens were brazed individually in a fixture, which was induction-heated. The fixture, in turn, heated the specimen by conduction. Induction heating plus conduction gave a more rapid heating than any other applicable method. Two chromel-alumel thermocouples were used to record the specimen temperature.

C. Heat Treating Equipment

Precipitation age hardening was accomplished in an electrically heated box type furnace with a retort designed to contain a protective atmosphere. The specimens to be aged were placed in the retort, which was then mechanically sealed. After suitable purging with argon, the retort was placed in the heated furnace and brought to temperature. A positive pressure of argon was maintained at all times during the heating and cooling cycles.

D. Mechanical Property Test Equipment

The Baldwin Universal Test Machine and the Marquardt Elevated Temperature Test Machine were used to determine mechanical properties.

VII. BRAZING PROCEDURES

A. Vacuum Brazing

1. Brazing Temperatures and Times

Brazing temperatures employed were in the manufacturers' recommended range for each individual braze alloy. Two temperature-time cycles were conducted for each braze alloy. The ability of the braze alloy to flow along the entire joint and metallographic examinations were utilized to determine the best of the two temperature-time cycles investigated. The actual test temperature-time cycles used are presented in Table IV.

2. Brazing Cycles

The retort containing the specimens was evacuated to one micron pressure before the heating period. During heating through a range of 700 to 1400°F the pressure varied from 5 to 16 microns due to outgassing. Retort pressure was held below one micron from approximately 1550°F up to final temperature throughout the remainder of each cycle.

3. Joint Design

A butt joint configuration was used to determine the braze joint mechanical properties. A joint clearance of 0.002 inch was used on all specimens. Two narrow straps were spot-tacked on each side of the specimen to hold the specified clearance. Figure 1 shows the butt joint specimen before and after brazing.

4. Braze Filler Metal Application

Both powder and foil braze filler metal forms were employed during the brazing tests. Foil was preplaced across the joint and held in place by an acrylic cement. The amount of foil used was three times that necessary to displace the joint volume. Powder was applied in the form of a slurry using a commercial cement having an acryloid resin base. Powdered alloy was applied across the joint in a ratio of approximately four times the gap volume of the joint.

B. Induction Brazing

1. Brazing Temperatures and Times

The brazing temperatures used were all within the recommended temperature range of the manufacturer. Hold times at temperature varied between 8 and 30 seconds. The actual test temperature and time for each specimen is shown in Table V.

2. Brazing Cycles

The specimens were individually brazed in a fixture, which was induction heated and, in turn, heated the specimen by conduction. After a thorough purging of the retort with argon, the specimen was heated to braze temperature, held for a required period of time, and then cooled. The braze temperature and cooling rates were measured by 2 chromel-alumel thermocouples attached to the specimen.

3. Joint Design

The butt joint configuration used for the induction-brazed specimens was the same as that used for the vacuum-brazed specimens (See Figure 1).

4. Braze Filler Metal Application

Both powder and foil braze filler metal forms were employed. Pre-placing of the filler metal was identical to the methods used for vacuum brazing.

VIII. RESULTS AND DISCUSSION

A. Rene' 41 to Rene' 41

(Tables VI and VII)

Joints made with AGC-1, AGC-4, and AGC-7 braze alloys were tensile-tested at room temperature and 1500°F. Prior to mechanical testing, all brazed specimens were given a 1650° aging treatment for four hours in argon atmosphere.

The highest average room temperature values were obtained for the AGC-1 and AGC-7 brazed joints--84 and 83 Ksi, respectively. The average room temperature result of the AGC-4 brazed joints was 67 Ksi, or approximately 20 percent lower. Failure occurred at the brazed joint in each specimen regardless of the braze alloy used.

The highest average tensile strengths obtained at 1500°F were those for the AGC-4 brazed joints--with an average of 35 Ksi. The AGC-1 and AGC-7 brazed joint strengths were 29 and 32 Ksi, respectively. Again, all failures occurred at the brazed joint.

Room temperature and 1500°F bend test results are listed. Room temperature results showed that the AGC-7 brazed joints had the greatest ductility with an average 78° bend (over a 10 t mandrel). Average values obtained from the AGC-1 and AGC-4 brazed joints were 50° and 61°, respectively.

Bend tests performed at 1500°F showed that the AGC-7 brazed joints had an average bend of 112°. The bends for the AGC-1 and AGC-4 brazed joints were 107° and 103°, respectively. These small differences are not considered significant.

B. Rene' 41 to L-605

(Tables VIII and IX)

Joints made with AGC-1, AGC-4, and AGC-7 braze alloys were tensile tested at room temperature and 1500°F. All brazed specimens were given a 1650°F aging treatment for four hours in an argon atmosphere prior to mechanical testing.

In four of the brazed joints tested at room temperature, the failure occurred in the 0.011-inch thick L-605 parent metal at values ranging from 66.0 to 87.5 Ksi. These stresses are below the normal parent metal strength of 100 Ksi for material of this thickness.

The lower ultimate tensile strengths can be attributed to three factors:

1. Effect of brazing thermal cycling

2. Edge effect (notch)

3. Misalignment of test fixtures

The highest average tensile strengths obtained at 1500°F were those for the AGC-7 brazed joints--an average of 27 Ksi. The AGC-1 and AGC-4 brazed joint strengths were 25 and 16 Ksi, respectively. All failures occurred at the brazed joints.

Room temperature and 1500°F bend tests showed AGC-7 brazed joints to have the highest average values with 87° and 77° bends, respectively. Room temperature average results of the AGC-1 and AGC-4 brazed joints were 81° and 67°, respectively. The AGC-1 and AGC-4 brazed joints were bend-tested at 1500°F and showed average values of 68° and 47°, respectively.

C. 6061 Aluminum to 6061 Aluminum

One of the major problems in brazing aluminum alloys is associated with the inherent tight oxide film formation on the aluminum surface, which tends to prevent wetting of the surface by the brazing alloy. The normal procedure to eliminate the oxide film is to apply a coating of flux on all surfaces to be brazed.

However, flux can be a potential corrosion hazard if exposed to any moisture and a post braze cleaning treatment to neutralize and to remove entrapped flux is not always 100 percent effective. Therefore, flux is undesirable for complex brazed assemblies where cleaning is difficult.

Both radiant heat vacuum and induction heating methods were employed for the aluminum brazing tests. Vacuum brazing was performed at a pressure of less than one micron. Induction brazing was conducted in a dry argon atmosphere (-90°F dew point). However, despite the precise fixturing and atmospheres incorporated, a good sound aluminum brazed joint suitable for mechanical testing could not be produced. This must be attributed to the fact that oxides of aluminum are only reducible at very high temperatures and with extremely low dew points. The equilibrium temperature for effective oxide reduction is far above the temperature used for brazing.

D. A110AT Titanium to A110AT Titanium

(Table X)

Both radiant heat vacuum and induction brazing were utilized. The two braze alloys used were AGC-7 and fine silver.

Specimens prepared with AGC-7 and fine silver were vacuum brazed for two minutes at temperatures of 1975° and 1775°F, respectively.

The long brazing cycle (including the cooling period) apparently caused excessive alloying between the titanium and the braze alloy, resulting in the formation of hard, brittle intermetallic compounds in the joint.

Induction brazing of the A110AT titanium specimens was performed in an argon atmosphere. Accessory equipment included a molecular sieve dryer to assure a consistently dry incoming gas. All specimens were individually brazed. The time at temperature varied between 8 to 30 seconds, with approximately 15 seconds required for the cooling period. As in vacuum brazing, the AGC-7 specimens were also embrittled. Subsequent evaluation of both vacuum and induction brazed AGC-7 specimens indicated that this braze alloy (Au, Ni, Pd) combined with the titanium to form a hard, brittle intermetallic compound. Results of furnace vacuum brazed specimens are not included due to the extreme brittleness exhibited.

The 100 percent Ag induction brazed specimens also were somewhat embrittled in the brazed joint, although not to such an extent as the AGC-7 braze joints.

E. 3Al-2.5V Titanium and Type 321 Stainless Steel, Thin Wall Tubing (Induction)

Preliminary experimental induction brazing studies were used on tube specimens of 3Al-2.5V titanium and Type 321 stainless steel material. The brazing alloys used for joining titanium to itself were fine silver (99.9% + purity) and AGC-7. A nickel base, chrome free, alloy (Coast Metals 52--AMS 4778) was used for joining stainless to stainless. Fine silver was used to join 3Al-2.5V titanium to stainless steel. This latter preliminary brazing study indicated that joining titanium to stainless steel using fine silver appears feasible.

F. Rene' 41, Induction Brazing

(Table XI)

Combinations of butt and lap 0.010- and 0.020-inch Rene' 41 sheets were experimentally brazed utilizing the induction process with inert gas (argon) as protective atmosphere. The equipment used was the same as that for 3Al-2.5V titanium and Type 321 stainless steel tubing. The brazing alloy was AGC-1 (50% gold, 25% nickel, 25% palladium).

Results of room temperature tests are noted in Table XI. Although they are not considered reliable design data, the results indicate the potentialities of the induction process.

G. Photomicrographs and Photographs

Figure 4-A is a photomicrograph (100x) of Rene' 41 furnace brazed to Rene' 41 utilizing the AGC-1 (50% Au, 25% Pd, 25% Ni) alloy. Note the displacement of base metal by the brazing alloy with virtually no intergranular diffusion. This may be attributed to preplacement of too large a volume of alloy and to inaccurate control of the braze temperature and hold time.

Figure 4-B is a photomicrograph (100x) of Rene' 41 furnace brazed to Rene' 41 utilizing AGC-4 (30% Au, 34% Pd, 36% Ni) alloy. Less displacement of the base metal is noted, but the reduced braze joint cross section could result in lower mechanical properties.

Figure 4-C is a photomicrograph (100x) of Rene' 41 furnace brazed to Rene' 41 utilizing AGC-7 (70% Au, 22% Ni, 8% Pd) alloy. The alloying and diffusion appear satisfactory, although the joint or abutting surfaces are misaligned.

Figure 5-A is a photomicrograph (100x) of Rene' 41 furnace brazed to L-605 utilizing the AGC-1 alloy. Severe displacement of the L-605 material by the braze alloy has occurred. This was attributable to the brazing technique.

Figure 5-B is a photomicrograph (100x) of Rene' 41 furnace brazed to L-605 utilizing the AGC-4 alloy. Displacement of the L-605 by the braze alloy plus misalignment of the abutting surface have occurred.

Figure 5-C is a photomicrograph (100x) of Rene' 41 furnace brazed to L-605 utilizing the AGC-7 alloy. Indications are that too strong an interface reaction has occurred due to the relatively long exposure at temperature. Misalignment of abutting surfaces is also noted.

Figure 6-A is a photomicrograph of A110AT furnace brazed to A110AT titanium utilizing fine silver (99.9+) alloy. Severe interdiffusion due to excessive alloying has resulted in formation of brittle intermetallic compounds.

Figure 6-B is a photomicrograph of A110AT furnace brazed to A110AT titanium utilizing the AGC-7 (70% Au, 22% Ni, 8% Pd) alloy. Severe displacement of the base metal has occurred plus indications of hard intermetallic compounds.

Figure 6-C is a photomicrograph of A110AT induction (inert gas) brazed to A110AT titanium utilizing fine silver. Interdiffusion is not so pronounced as in Figure 6-A. Embrittlement did occur.

Figure 7 is an assembly incorporating the joining of 0.002-inch wall titanium to titanium, titanium to stainless steel (0.0025-inch wall), and stainless to stainless. Two of the baffles are titanium, and two are stainless steel. This test assembly was made to determine the feasibility of controlling the induction process in brazing thin wall similar and dissimilar material combinations. The brazing alloys were fine silver for joining titanium to titanium and titanium to stainless steel and AMS 4778 (nickel base) for joining stainless to stainless.

Figure 8 shows the configuration and the results of brazing 0.005-inch baffles to 0.0025-inch wall stainless steel tubing. The base metal retained its cold-worked properties except in the area of rupture. Rupture occurred adjacent to the baffle, and, in addition, the tube-baffle junction formed stress concentrations.

Figures 9 to 12 show the effects of short and prolonged aging at anticipated service temperatures of brazed 0.0025-inch wall Type 321 stainless steel tubing contemplated for heat exchanger application.

Figure 9 indicates that short time aging (15 minutes at 1400°F) of Type 321 stainless steel at 1400°F does not affect the properties of the base metal. Some preliminary surface scaling is observable.

Figure 10 (16 hours at 1400°F) indicates a significant effect (decline) on the physical properties. Surface scaling is more pronounced.

Figure 11 indicates that short time aging (15 minutes at 1600°F) has no effect on the properties of the base metal.

Figure 12 (16 hours at 1600°F) was not tested due to complete embrittlement of the thin wall tubing.

Parallel oxidation tests of 0.030-inch Type 321 stainless steel indicated that this material possessed good oxidation resistance. The catastrophic decline of the above thin wall tubing (after exposure) is quite significant, and further study is required in this area.

IX. CONCLUSIONS

The properties exhibited by the vacuum brazed Rene' 41 and L-605 specimens were satisfactory for design requirements even though they were lower than the properties obtained in previous brazing studies.

The induction brazing of Rene' 41 appears promising, but further development is required, particularly for various joint configurations.

The brazing of titanium indicates the need for a more extensive investigation, particularly in the use of the induction (quick heating) process. Experiments should also be conducted using more compatible brazing alloys.

Additional studies are required to determine the oxidation resistance of thin-wall Type 321 stainless steel tubing.

TABLE I

CHEMICAL COMPOSITION

Material	Chemical Composition (percent)	
Rene' 41	Chromium	18.00 - 20.00
	Cobalt	10.00 - 12.00
	Molybdenum	9.00 - 10.50
	Iron	5.0 max.
	Titanium	3.00 - 3.30
	Aluminum	1.40 - 1.60
	Silicon	0.50 max.
	Carbon	0.12 max.
	Manganese	0.10 max.
	Boron	0.003 - 0.010
	Sulphur	0.015 max.
	Nickel	Balance
L-605	Nickel	9.00 - 11.00
	Chromium	19.00 - 21.00
	Tungsten	14.00 - 16.00
	Iron	3.00 max
	Carbon	0.05 - 0.15
	Silicon	1.00 max.
	Manganese	1.00 - 2.00
	Cobalt	Balance
6061	Copper	0.25
	Silicon	0.60
	Manganese	1.00
	Chromium	0.25
	Aluminum	Balance
A110AT	Aluminum	5.00
	Tin	2.50
	Titanium	Balance

TABLE II

SUMMARY OF BRAZING ALLOYS

Brazing Alloy	Producer	Composition (%)	Form	Melting Point (°F)	Normal Range of Braze Temperature (°F)
AGC-1	Western Gold and Platinum	Au - 50 Pd - 25 Ni - 25	Powder	2035	2075 to 2100
AGC-4	Western Gold and Platinum	Au - 30 Pd - 34 Ni - 36	Powder	2120	2140 to 2175
AGC-7	Western Gold and Platinum	Au - 70 Pd - 8 Ni - 22	Powder	1910	1950 to 1975
Alcoa 718 (AMS 4185)	Aluminum Co. of America	Si - 12 Al - Bal.	Powder & foil	1075	1095 to 1105
Fine silver	Handy & Harmon	Ag - 100	Powder & foil	1760	1780 to 1825

TABLE III

CLEANING PROCEDURES

Base Metal	Cleaning Procedure Employed
Rene' 41 L-605	Nitric acid 25 to 30 oz Hydrofluoric acid 2 to 4 oz Water To make 1 gal Temperature = Ambient to 140°F Time = 20 minutes maximum Rinse = Cold running clean water followed by hot water rinse to facilitate rapid drying
6061	Oakite 34 12 to 16 oz/gal water Temperature = Ambient Time = 5 to 20 minutes Rinse = Cold running clean water followed by hot water rinse to facilitate rapid drying
A110AT	Nitric acid 50 oz Hydrofluoric acid 5 oz Water To make 1 gal Temperature = Ambient Time = 20 minutes maximum Rinse = Cold running clean water followed by hot water rinse to facilitate rapid drying

TABLE IV

TEST TEMPERATURES AND TIMES -- VACUUM FURNACE BRAZING

Base Material Combination	Braze Alloy	Alloy Form	Braze Conditions	
			Temperature (°F)	Time (min)
Rene' 41 to Rene' 41	AGC 1	Powder	2050	2
Rene' 41 to L-605	AGC 1	Powder	2050	2
Rene' 41 to Rene' 41	AGC 4	Powder	2140	2
Rene' 41 to L-605	AGC 4	Powder	2140	2
Rene' 41 to Rene' 41	AGC 7	Powder	1950	2
Rene' 41 to L-605	AGC 7	Powder	1950	2
A110AT to A110AT	AGC 7	Powder	1950	2
6061 to 6061	4185	Powder & foil	1095	2
A110AT to A110AT	100% Ag	Powder & foil	1760	2
Rene' 41 to Rene' 41	AGC 1	Powder	2075	2
Rene' 41 to L-605	AGC 1	Powder	2075	2
Rene' 41 to Rene' 41	AGC 4	Powder	2150	2
Rene' 41 to L-605	AGC 4	Powder	2150	2
Rene' 41 to Rene' 41	AGC 7	Powder	1975	2
Rene' 41 to L-605	AGC 7	Powder	1975	2
A110AT to A110AT	AGC 7	Powder	1975	2
6061 to 6061	4185	Powder & foil	1115	2
A110AT to A110AT	100% Ag	Powder & foil	1775	2

TABLE V

INDUCTION BRAZING OF A110AT TITANIUM TO A110AT TITANIUM
SHOWING TEMPERATURE AND TIME CYCLES

Specimen No.	Purge Time (min)	Brazing Alloy	Brazing Temperature (°F)	Time at Temperature (sec)	Cooling Time (sec)
234 G	2	100% Ag	1775	20	15
235 G	2	100% Ag	1775	8	15
236 G	2	100% Ag	1775	20	15
237 G	2	100% Ag	1775	29	15
238 G	2	100% Ag	1775	12	15
239 G	2	100% Ag	1775	20	15
240 G	2	100% Ag	1775	22	15
241 G	2	100% Ag	1775	15	15
242 G	2	100% Ag	1775	12	15
243 G	2	100% Ag	1775	12	15
244 G	2	100% Ag	1775	11	15
245 G	2	100% Ag	1775	14	15
246 G	2	AGC-7	1975	10	15
247 G	2	AGC-7	1975	15	15
248 G	2	AGC-7	1975	30	15
249 G	2	AGC-7	1975	20	15
250 G	2	AGC-7	1975	20	15
251 G	2	AGC-7	1975	18	15
252 G	2	AGC-7	1975	21	15
253 G	2	AGC-7	1975	23	15
254 G	2	AGC-7	1975	19	15
255 G	2	AGC-7	1975	20	15
256 G	2	AGC-7	1975	20	15
257 G	2	AGC-7	1975	17	15

TABLE VI

TENSILE PROPERTIES OF VACUUM BRAZED RENE' 41 SHEET
AGED 1650°F, 4 HOURS, IN ARGON ATMOSPHERE

Test Conditions:

Specimen = Butt joint, 0.002-in. gap
Strain rate = 0.01 in./in./sec to rupture
Heating method = Furnace

Specimen No.	Thickness (in.)	Brazing Alloy	Brazing Conditions Temperature (°F)	Brazing Conditions Time (min)	Test Temperature (°F)	Ultimate Tensile Strength (Ksi)	Elongation (% in 2 in.)	Location of Fracture
1	0.011	AGC-1	2075	2	RT	74.5	--	Brazed joint
2	0.011	AGC-1	2075	2	RT	70.7	--	Brazed joint
3	0.011	AGC-1	2075	2	RT	106.5	--	Brazed joint
4	0.011	AGC-1	2075	2	1500	29.6	--	Brazed joint
5	0.011	AGC-1	2075	2	1500	30.1	--	Brazed joint
6	0.011	AGC-1	2075	2	1500	27.2	--	Brazed joint
1	0.011	AGC-4	2140	2	RT	73.2	--	Brazed joint
2	0.011	AGC-4	2140	2	RT	87.2	--	Brazed joint
3	0.011	AGC-4	2140	2	RT	40.4	--	Brazed joint
4	0.011	AGC-4	2140	2	1500	31.5	--	Brazed joint
5	0.011	AGC-4	2140	2	1500	28.0	--	Brazed joint
6	0.011	AGC-4	2140	2	1500	45.8	--	Brazed joint
1	0.011	AGC-7	1975	2	RT	73.4	--	Brazed joint
2	0.011	AGC-7	1975	2	RT	60.1	--	Brazed joint
3	0.011	AGC-7	1975	2	RT	115.3	0.2	Brazed joint
4	0.011	AGC-7	1975	2	1500	33.7	--	Brazed joint
5	0.011	AGC-7	1975	2	1500	29.1	--	Brazed joint
6	0.011	AGC-7	1975	2	1500	33.2	--	Brazed joint

RT = Room temperature

TABLE VII

BEND TESTS OF VACUUM BRAZED RENE' 41 SHEET
AGED 1650°F, 4 HOURS, ARGON ATMOSPHERE

Test Conditions:

Specimen = Butt joint, 0.002-in. gap
Bend diameter = 10 td
Heating method = Furnace

Specimen No.	Thickness (ins.)	Brazing Alloy	Brazing Conditions Temperature (°F)	Time (min)	Test Temperature (°F)	Bend Angle (°)	Remarks
1	0.011	AGC-1	2075	2	RT	30	Cracked
2	0.011	AGC-1	2075	2	RT	55	Cracked
3	0.011	AGC-1	2075	2	RT	64	Cracked
4	0.011	AGC-1	2075	2	1500	70	Cracked
5	0.011	AGC-1	2075	2	1500	140	Cracked
6	0.011	AGC-1	2075	2	1500	110	Cracked
1	0.011	AGC-4	2140	2	RT	70	Cracked
2	0.011	AGC-4	2140	2	RT	60	Cracked
3	0.011	AGC-4	2140	2	RT	53	Cracked
4	0.011	AGC-4	2140	2	1500	110	Cracked
5	0.011	AGC-4	2140	2	1500	110	Cracked
6	0.011	AGC-4	2140	2	1500	90	Cracked
1	0.011	AGC-7	1975	2	RT	73	Cracked
2	0.011	AGC-7	1975	2	RT	70	Cracked
3	0.011	AGC-7	1975	2	RT	90	O K
4	0.011	AGC-7	1975	2	1500	105	Cracked
5	0.011	AGC-7	1975	2	1500	140	Cracked
6	0.011	AGC-7	1975	2	1500	90	Cracked

RT = Room temperature

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TABLE VIII

TENSILE PROPERTIES OF RENE' 41 SHEET VACUUM BRAZED TO L-605 SHEET
AGED 1650°F, 4 HOURS, ARGON ATMOSPHERE

Test Conditions:

Specimen = Butt joint, 0.002-in. gap
Strain rate = 0.1 in./in./sec to rupture
Heating method = Furnace

Specimen No.	Thickness (ins.)	Brazing Alloy	Brazing Conditions Temperature (°F)	Brazing Conditions Time (min)	Test Temperature (°F)	Ultimate Tensile Strength (Ksi)	Elongation (% in 2 in.)	Location of Fracture
1	0.011	AGC-1	2075	2	RT	72.4	2.0	Brazed joint
2	0.011	AGC-1	2075	2	RT	69.6	1.5	Brazed joint
3	0.011	AGC-1	2075	2	RT	87.7	4.0	Brazed joint
4	0.011	AGC-1	2075	2	1500	23.4	--	Brazed joint
5	0.011	AGC-1	2075	2	1500	30.9	--	Brazed joint
6	0.011	AGC-1	2075	2	1500	20.8	--	Brazed joint
1	0.011	AGC-4	2140	2	RT	55.2	0.7	Brazed joint
2	0.011	AGC-4	2140	2	RT	82.5	5.0	L-605, 1/4-in. from joint
3	0.011	AGC-4	2140	2	RT	74.6	2.0	Brazed joint
4	0.011	AGC-4	2140	2	1500	12.9	--	Brazed joint
5	0.011	AGC-4	2140	2	1500	15.3	--	Brazed joint
6	0.011	AGC-4	2140	2	1500	21.1	--	Brazed joint
1	0.011	AGC-7	1975	2	RT	66.0	3.5	L-605, 1/8-in. from joint
2	0.011	AGC-7	1975	2	RT	87.5	2.5	L-605, 3/8-in. from joint
3	0.011	AGC-7	1975	2	RT	73.3	3.0	L-605, 3/8-in. from joint
4	0.011	AGC-7	1975	2	1500	--*		
5	0.011	AGC-7	1975	2	1500	27.8	--	Brazed joint
6	0.011	AGC-7	1975	2	1500	25.2	--	Brazed joint

* = No value
RT = Room temperature

TABLE IX

BEND TESTS OF RENE' 41 SHEET VACUUM BRAZED TO L-605 SHEET
AGED 1650°F, 4 HOURS, ARGON ATMOSPHERE

Test Conditions:

Specimen = Butt joint, 0.002-in. gap
Bend diameter = 10 td
Heating method = Furnace

Specimen No.	Thickness (ins.)	Brazing Alloy	Brazing Conditions Temperature (°F)	Brazing Conditions Time (min)	Test Temperature (°F)	Bend Angle (°)	Remarks
1	0.011	AGC-1	2075	2	RT	70	Cracked
2	0.011	AGC-1	2075	2	RT	83	Cracked
3	0.011	AGC-1	2075	2	RT	90	O K
4	0.011	AGC-1	2075	2	1500	75	Cracked
5	0.011	AGC-1	2075	2	1500	70	Cracked
6	0.011	AGC-1	2075	2	1500	80	Cracked
1	0.011	AGC-4	2140	2	RT	50	Cracked
2	0.011	AGC-4	2140	2	RT	90	O K
3	0.011	AGC-4	2140	2	RT	60	Cracked
4	0.011	AGC-4	2140	2	1500	50	Cracked
5	0.011	AGC-4	2140	2	1500	50	Cracked
6	0.011	AGC-4	2140	2	1500	40	Cracked
1	0.011	AGC-7	1975	2	RT	90	O K
2	0.011	AGC-7	1975	2	RT	90	O K
3	0.011	AGC-7	1975	2	RT	80	Cracked
4	0.011	AGC-7	1975	2	1500	75	Cracked
5	0.011	AGC-7	1975	2	1500	70	Cracked
6	0.011	AGC-7	1975	2	1500	85	Cracked

RT = Room temperature

TABLE X

TENSILE PROPERTIES OF INDUCTION BRAZED A110AT TITANIUM SHEET

Brazing Alloy = Fine Silver

Test Conditions:

Specimen = Butt joint, 0.002-in. gap
Strain rate = 0.01 in./in./sec to rupture
Heating method = Furnace

Specimen No.	Thickness (ins.)	Brazing Conditions		Test Temperature (°F)	Ultimate Tensile Strength (Ksi)	Location of Fracture
		Temperature (°F)	Time (min)			
1	0.031	1775	10	RT	19.8	Brazed joint
2	0.031	1775	20	RT	17.0	Brazed joint
3	0.031	1775	30	RT	21.8	Brazed joint
1	0.031	1775	15	700	16.4	Brazed joint
2	0.031	1775	20	700	9.7	Brazed joint
3	0.031	1775	23	700	13.1	Brazed joint

RT = Room temperature

TABLE XI

RESULTS OF PRELIMINARY TESTS OF INDUCTION BRAZED RENE' 41 SHEET

(Specimens are listed in Table I)

Specimen No.	Thickness Combustion (ins.)	Over-Lap	Brazing Alloy	Fracture Area	Tensile Ultimate Strength (Ksi)	Ultimate Shear (Ksi)
1	0.020/0.010	(2T)	AGC-1	Base metal	106	53
4	0.020/0.010	(2T)	AGC-1	Base metal	111	55.5
5	0.020/0.020	(Butt)	AGC-1	Base metal	105	--
7	0.020/0.010	(Butt)	AGC-1	Base metal	87	--
8	0.010/0.010	(1T)	AGC-1	Base metal	113	113
6	0.010/0.020	(1T)	AGC-1	Base metal	122	122
9	0.020/0.020	(1/2T)	AGC-1	Base metal	85	170
13	0.020/0.020	(1T)	AGC-1	Base metal	116	116
20	0.010/0.010	(4T)	AGC-1	Base metal	102	26
21	0.010/0.010	(3T)	AGC-1	Base metal	113	37.7
24	0.020/0.020	(1T)	AGC-1	Base metal	152	152
25	0.020/0.020	(4T)	AGC-1	Base metal	161	40
27	0.010/0.020	(4T)	AGC-1	Base metal	120	30
28	0.010/0.010	(6T)	AGC-1	Base metal	100	16.7
29	0.010/0.010	(16T)	AGC-1	Base metal	118	7.4
30	0.010/0.010	(10T)	AGC-1	Base metal	107	10.7
33	0.020/0.020	(2T)	AGC-1	Base metal	147	73.5
34	0.020/0.020	(1T)	AGC-1	Base metal	162	162

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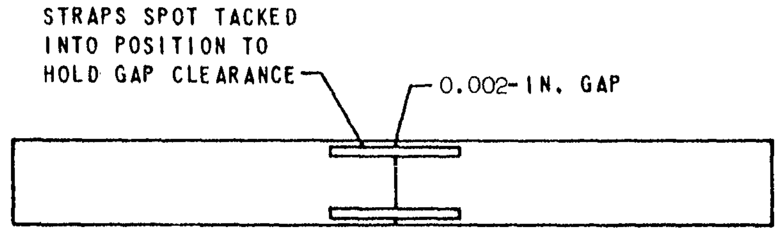
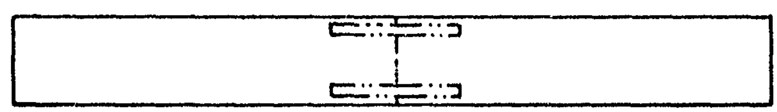
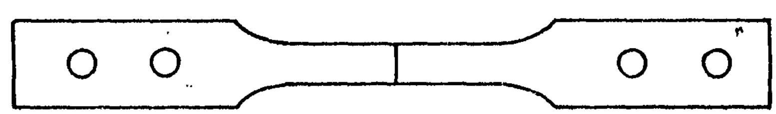
TENSILE TEST SPECIMENS FOR BRAZED SHEET MATERIAL



A. BEFORE BRAZE

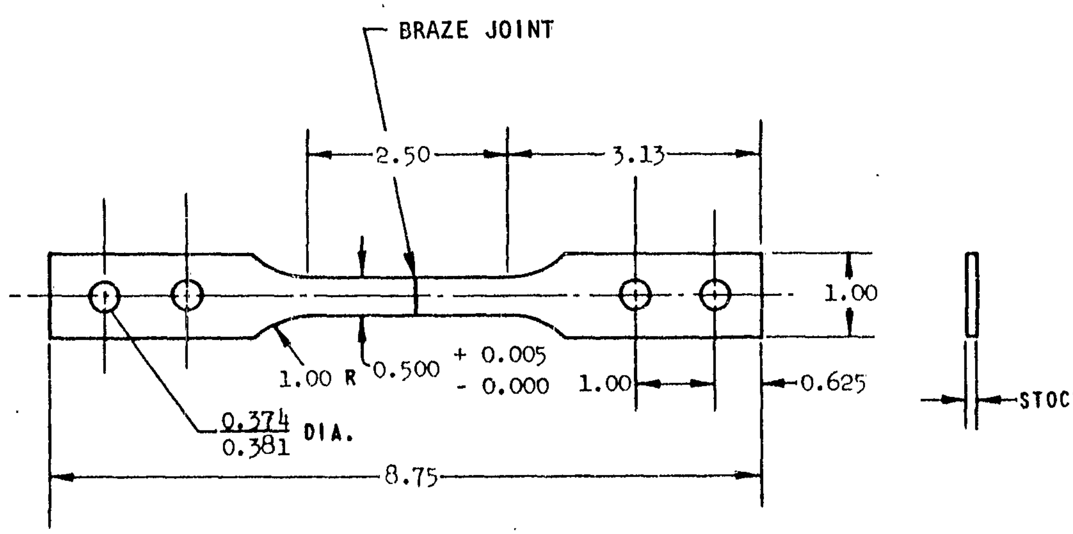


B. AFTER BRAZE



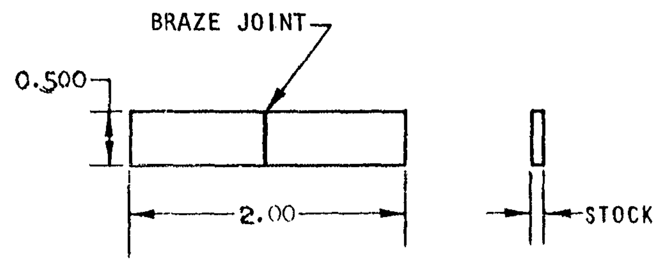
C. STANDARD SPECIMEN

STANDARD TENSILE TEST SPECIMEN FOR SHEET MATERIAL



NOTE:
ALL DIMENSIONS IN INCHES

STANDARD BEND TEST SPECIMEN FOR SHEET MATERIAL



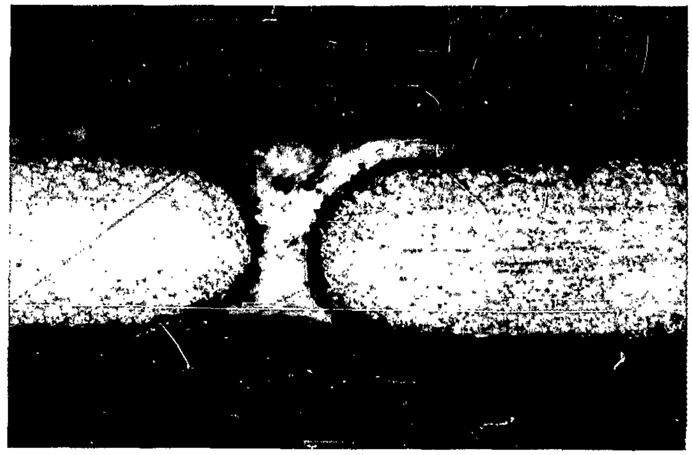
NOTE:

ALL DIMENSIONS IN INCHES

A. Rene' 41 vacuum brazed to Rene' 41 with AGC-1 braze alloy

Braze temp. 2075°F
Braze time 2 min.

100X



B. Rene' 41 vacuum brazed to Rene' 41 with AGC-4 braze alloy

Braze temp. 2140°F
Braze time 2 min.

100X

C. Rene' 41 vacuum brazed to Rene' 41 with A .C-7 braze alloy

Braze temp. 1975°F
Braze time 2 min.

100X

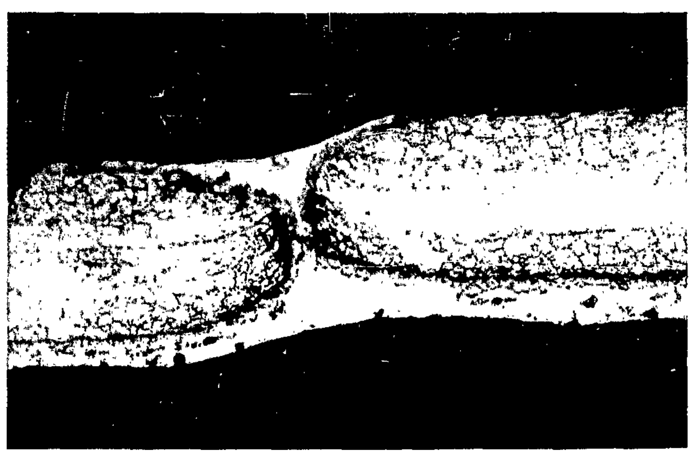
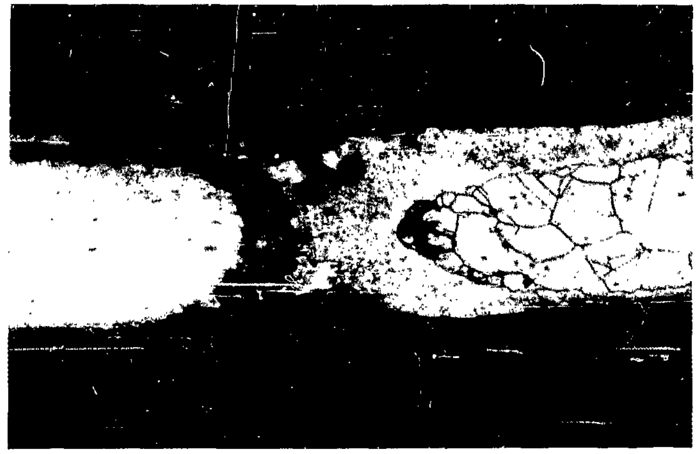


FIGURE 4 - Rene' 41 Vacuum Brazed to Rene' 41 with Several Brazing Alloys

A. Rene' 41 vacuum brazed to L-605 with AGC-1 braze alloy

Braze temp. 2075°F
Braze time 2 min.

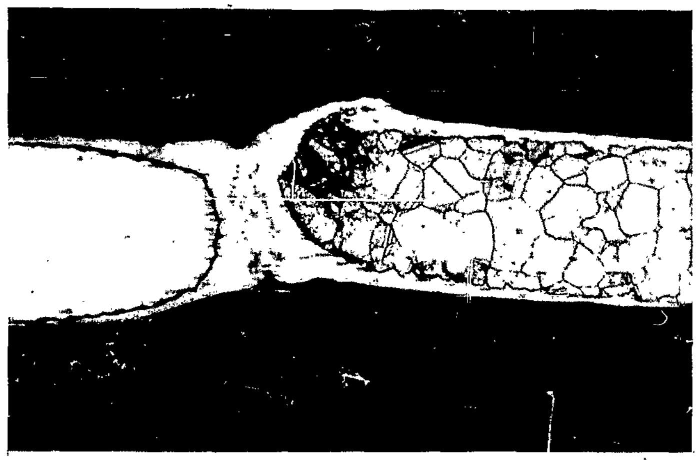
100X



B. Rene' 41 vacuum brazed to L-605 with AGC-4 braze allo.

Braze temp. 2140°F
Braze time 2 min.

100X



C. Rene' 41 vacuum brazed to L-605 with AGC-7 braze alloy

Braze temp. 1975°F
Braze time 2 min.

100X

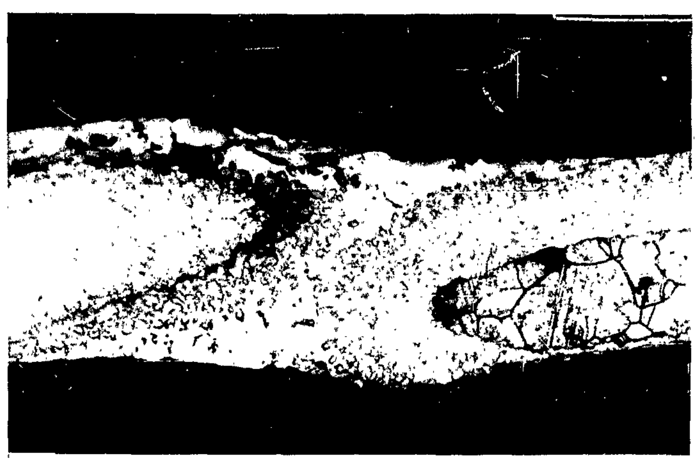


FIGURE 5 - Rene' 41 Vacuum Brazed to L-605 with Several Brazing Alloys

A. A110AT Ti vacuum brazed to A110AT Ti with 100% Ag alloy

Braze temp. 1775°F
Braze time 2 min.

40X

B. A110AT Ti vacuum brazed to A110AT Ti with AGC 7 braze alloy

Braze temp. 1975°F
Braze time 2 min.

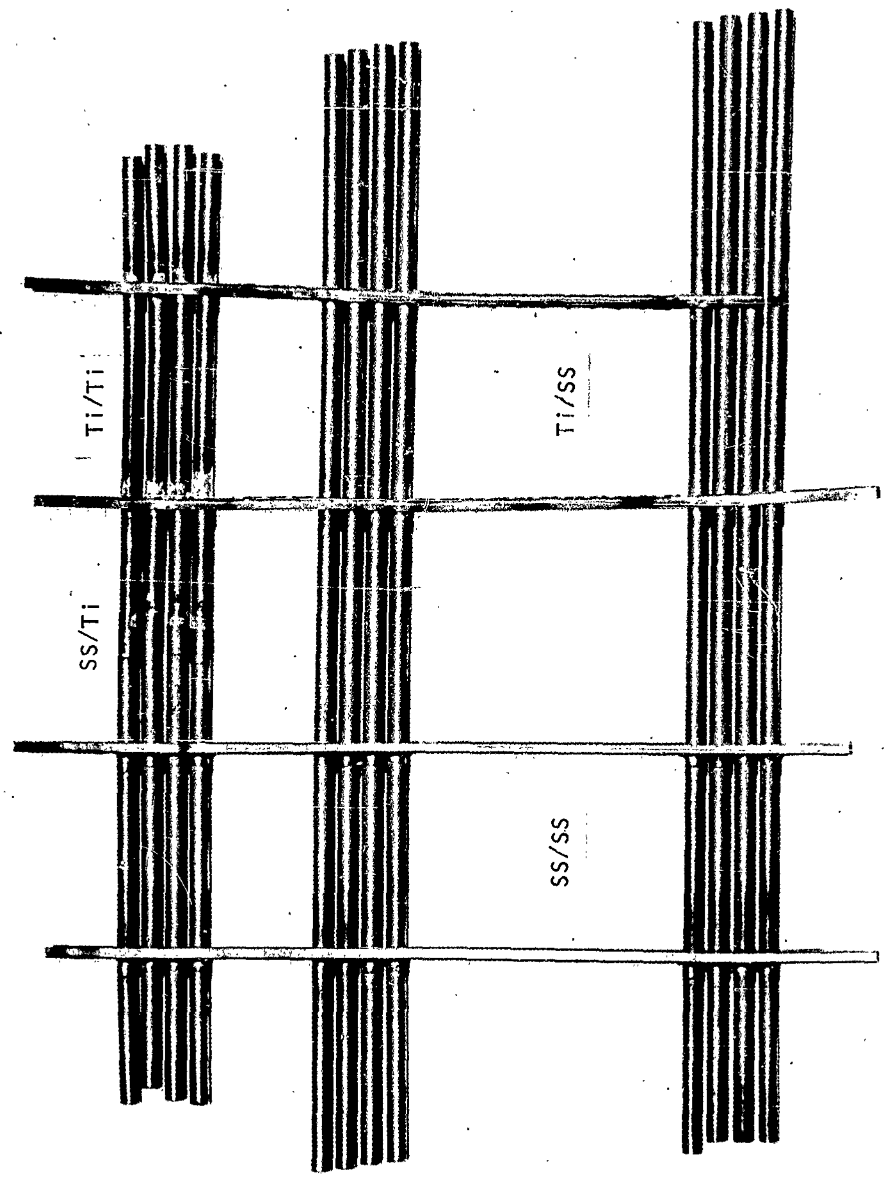
40X

C. A110AT Ti induction brazed to A110AT Ti with 100% Ag alloy

Braze temp. 1750°F
Braze time 20 sec.

40X

FIGURE 6 - A110AT Titanium Vacuum Brazed to A110AT Titanium with Several Brazing Alloys



NEG. CA4111-42

FIGURE 7 - Induction Brazed Assemblies of 0.002- and 0.0025-inch Wall Stainless Steel and Titanium Tubing

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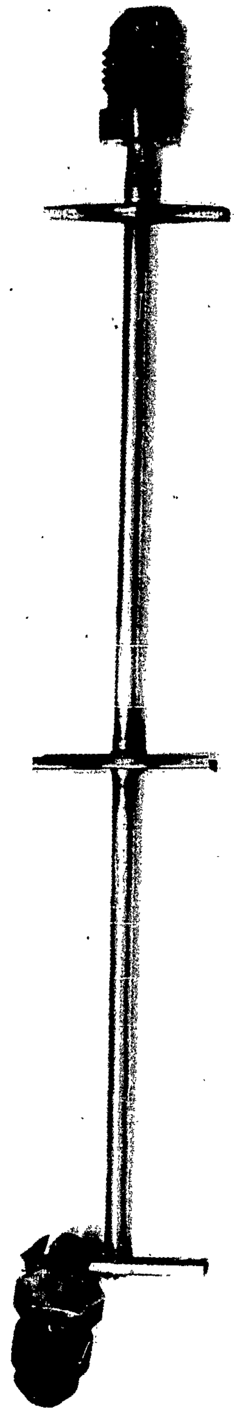

NEG. 4111-35

FIGURE 8 - Induction Brazed Assembly of 0.0025-inch Wall Type 321 Stainless Steel Tubing After Pressure to 3450 psi

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NEG. CA4111-43

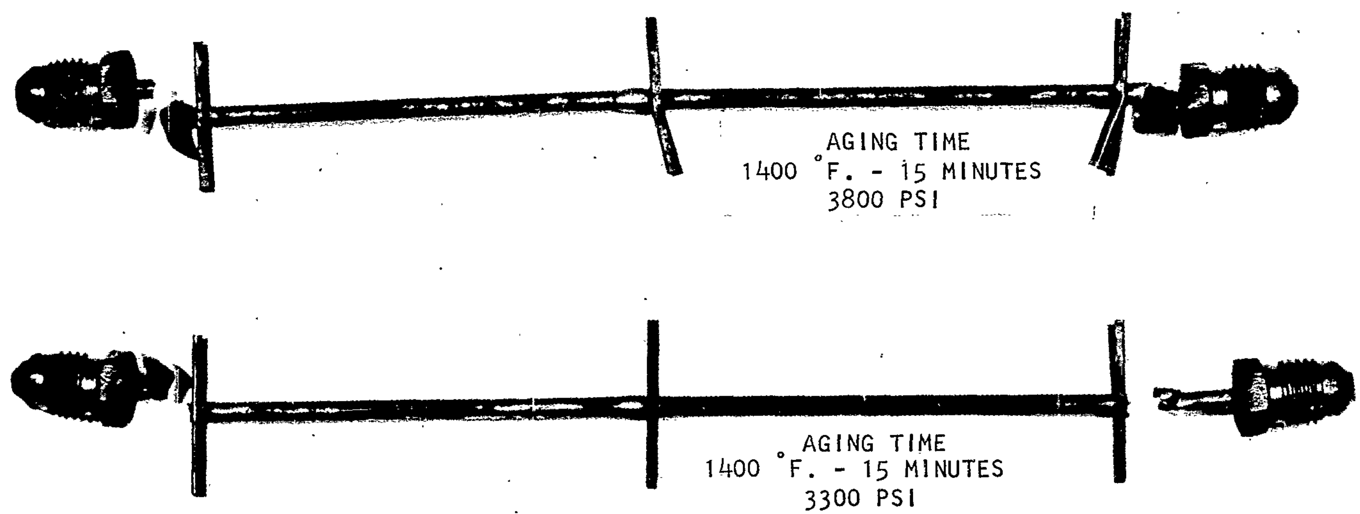


FIGURE 9 - Induction Brazed Assemblies of 0.0025-inch Wall Type 321 Stainless Steel Tubing After Pressure Tests

NEG. CA4111-44

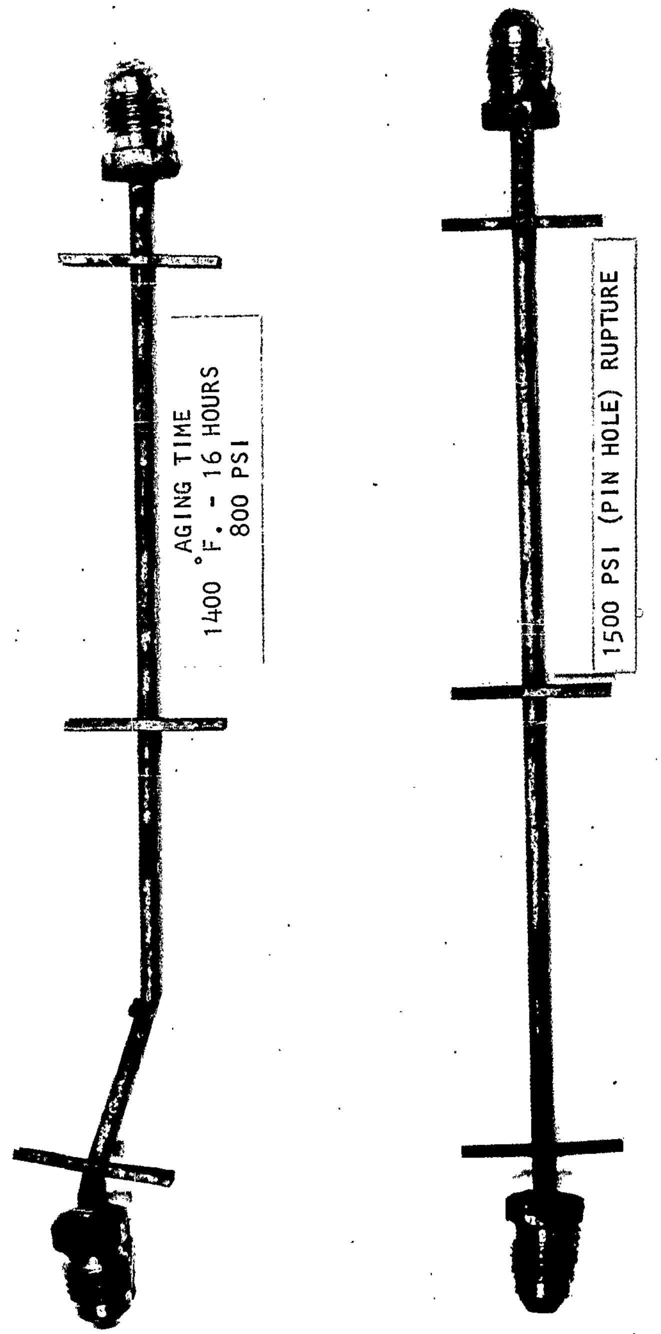
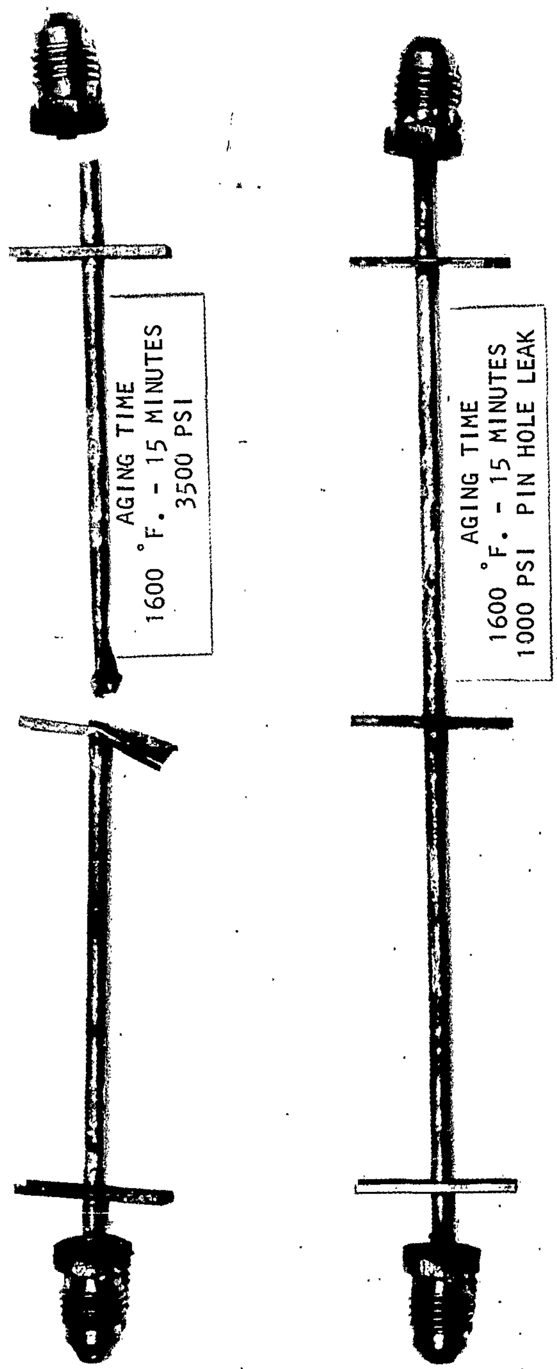


FIGURE 10 - Induction Brazed Assemblies of 0.0025-inch Wall Type 321 Stainless Steel Tubing After Pressure Tests



NEG. CA4111-45

FIGURE 11 - Induction Brazed Assemblies of 0.0025-inch Wall Type 321 Stainless Steel Tubing After Pressure Tests

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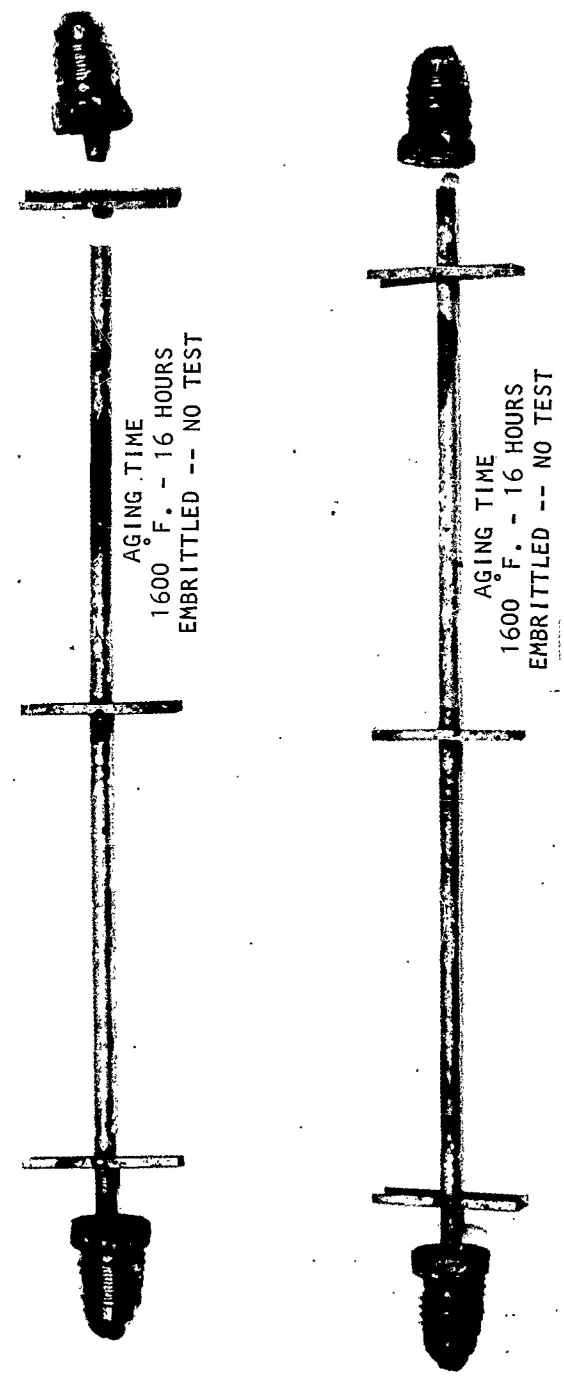

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FIGURE 12 - Induction Brazed Assemblies of 0.0025-inch Wall Type 321 Stainless Steel Tubing, Embrittled and Not Pressure Tested

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